



# **US LHC ACCELERATOR PROJECT** ***brookhaven - fermilab - berkeley***

Bunch by bunch measurement and optimization  
of luminosity in LHC

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A team has been assembled to address IR absorber instrumentation issues:

- storage ring operations
- beam-beam interaction
- detector physics
- radiation effects
- signal processing and data acquisition
- hardware design

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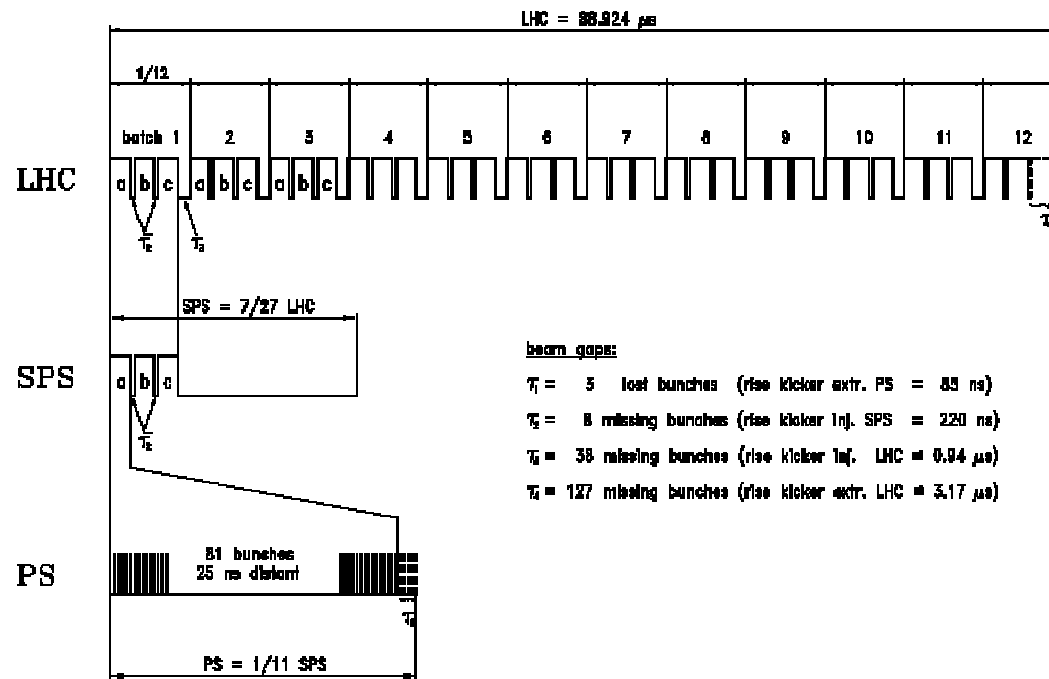


## Outline

- Requirements for Lumi measurement
- IR absorbers
- Concept for Lumi measurement
- Ionization chamber properties
- Electronics
- Integration times
- ~~Backgrounds~~
- Beam test plan
- Summary



# LHC bunch structure (Yellow Book version)



- There are 3564 bunch spaces in LHC, 2835 are occupied (b) and 729 are empty (e) to allow for kicker rise times

$$\begin{aligned}
 3564 &= 12 \times 297 \\
 &= 11 \times [3 \times (81b + 8e) + 30e] + [2 \times (81b + 8e) + 119e]
 \end{aligned}$$



## Requirements for LHC luminosity instrumentation (Lumi Optimization in LHC Workshop, CERN, 16-17 Apr. 1999)

- Absolute L measurement with  $\delta L/L \sim 5\%$  for  $L > 10^{30} \text{ cm}^{-2}\text{sec}^{-1}$
- Cross calibration with LHC experiment measurements of L (every few months)
- Sensitivity of L measurement to variations of IP position ( $x^*, y^* < 1\text{mm}$ ) and crossing angle ( $x^*, y^* < 10\mu\text{rad}$ ) less than 1%
- Dynamic range with “reasonable” acquisition times for 1% precision to cover  $10^{28} \text{ cm}^{-2}\text{sec}^{-1}$  to  $10^{34} \text{ cm}^{-2}\text{sec}^{-1}$
- Capable of use to keep machine tuned within  $\sim 2\%$  of optimum L
- Bandwidth 40 MHz to resolve the luminosity of individual bunches
- Backgrounds less than 10% of the L signal and correctable

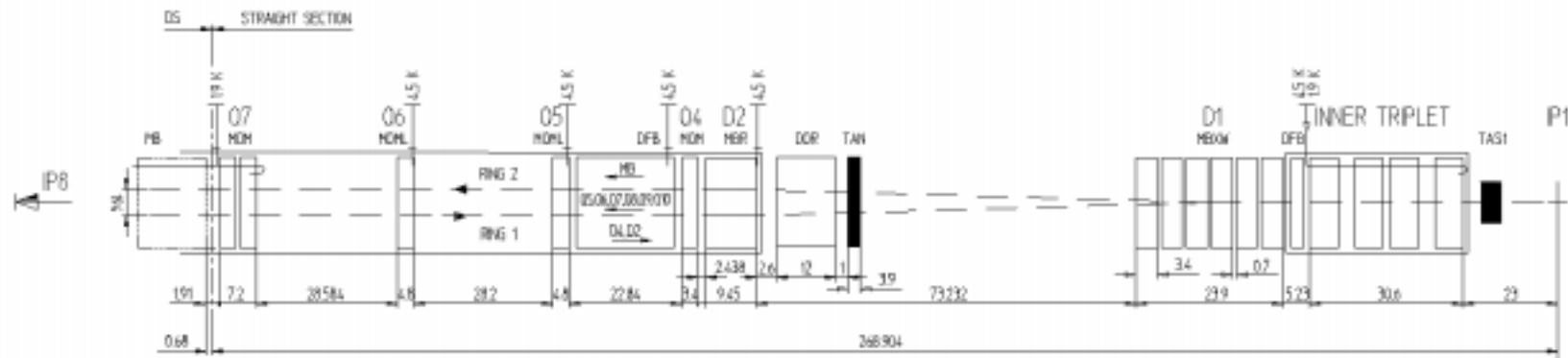


## IR absorbers

- The high luminosity of LHC requires special purpose absorbers being designed and built at LBNL to protect superconducting magnets from IP radiation
- Absorbed radiation power  $\sim$  luminosity, our goal is to take advantage of the existence of these absorbers to provide a machine operations tool for optimizing the luminosity of the LHC
- Absorption of IR collision products and induced activation are being calculated with the MARS code by N. Mokhov at FNAL
- Practical implementation of a luminosity monitor requires attention to radiation hardness
  - peak power density =  $5\text{-}10\text{W/kgm} \Rightarrow 50\text{-}100\text{MGy (5-10GRad)/oper yr}$



## Nominal locations of the front quadrupole (TAS) and neutral (TAN) absorbers in IP1(5), v6.0

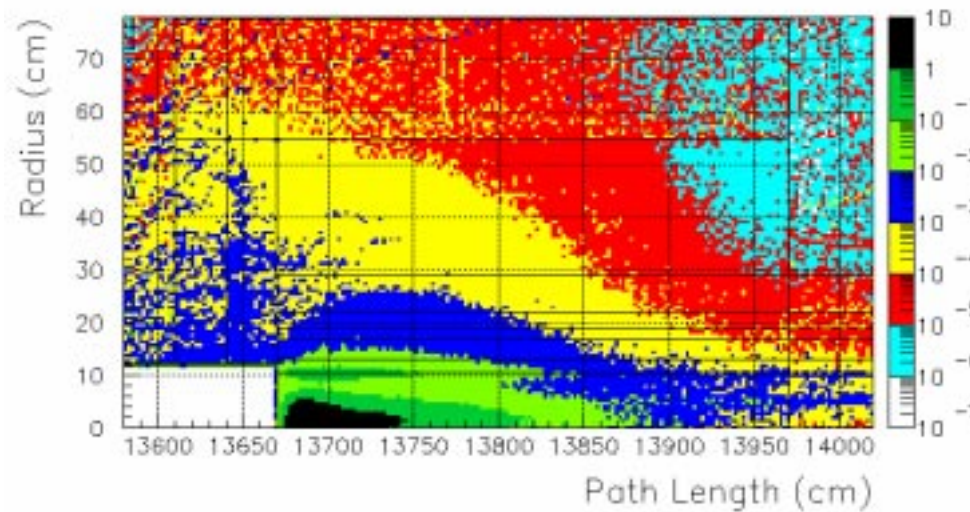


- The TAS absorbs forward collision products that have escaped the beam tube in front of Q1 (mostly charged pions and photons)
- The TAN absorbs forward neutral collision products (mostly neutrons and photons) and is placed in front of the outer beam separation dipole D2



## TAN power deposition (W/kgm)

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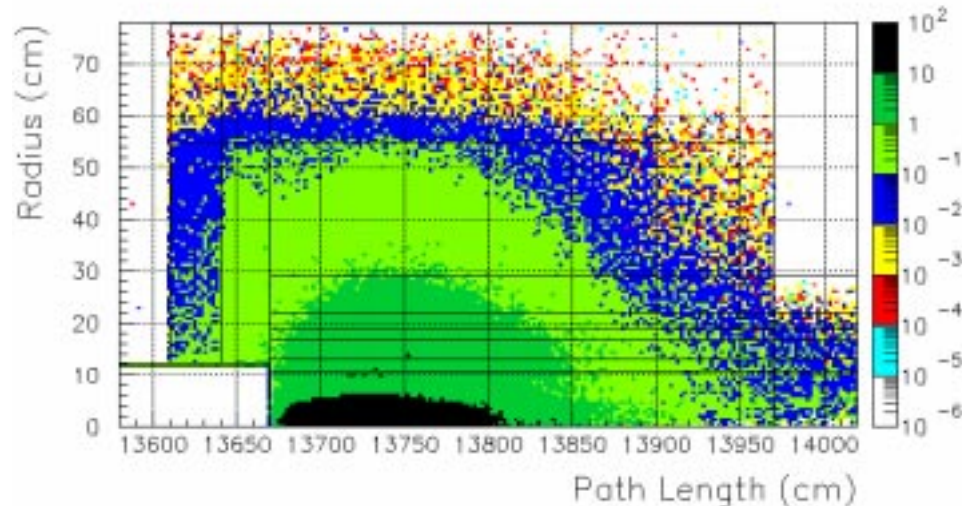


- Peak pwr density 1-10 W/kgm (location of ionization chamber)
- A 3m radiation hard cable will allow electronics to be located in a region with pwr density  $< 10^{-5}$  W/kgm (100 Gy/oper yr)



## TAN activation at 30d/1d (mSv/hr)

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- Contact dose  $< 0.1$  mSv/hr at outer  $r = 55$  cm and back surfaces of the TAN (ok to stand in region per CERN guidelines)
- Contact dose inside the inner absorber box exceeds 1 mSv/hr (requires remote handling per CERN guidelines)
- Our goal is to design a detector that can be operated indefinitely without maintenance or replacement



## Incident particle fluxes per pp interaction

	(a) TAN			(b) TAS		
Particle type	$\langle n \rangle$	$\langle E \rangle$ (GeV)	$\langle n \rangle \langle E \rangle$ (GeV)	$\langle n \rangle$	$\langle E \rangle$ (GeV)	$\langle n \rangle \langle E \rangle$ (GeV)
Neutral hadrons	.33	2185.	725	.58	261.	152
Protons	.06	1215.	73	.29	292.	83
Charged Pions	.71	125.	88	6.8	159.	1081
Photons	151	4.87	735	8.3	87.	725
Electron/positron	12.5	.66	8.25	-	-	-
Muons	.014	25	.35	.06	33	2

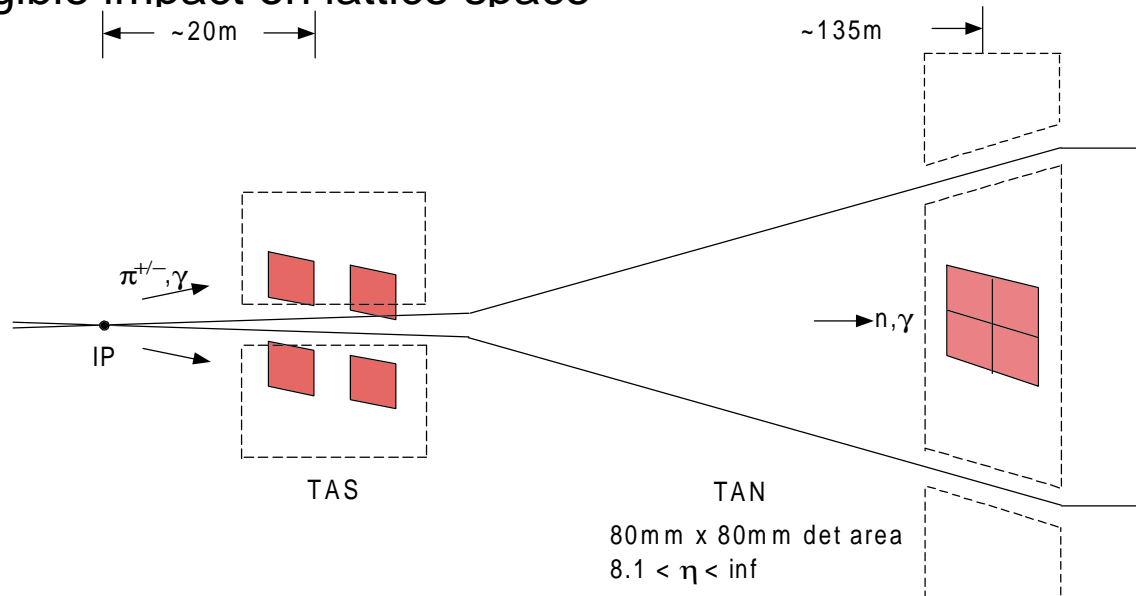
- An example: TAN neutrons

$$\begin{aligned}
 L &= 10^{34} \text{ cm}^{-2} \text{ s}^{-1}, \sigma_{\text{inel}} = 80 \text{ mb} & \Rightarrow 8 \times 10^8 \text{ pp int/s} \\
 \langle n \rangle &= 0.33 \text{ neutrons/pp int} & \Rightarrow 2.6 \times 10^8 \text{ n/s} \\
 f &= 40 \text{ MHz bunch xing} & \Rightarrow 6.6 \text{ n/bunch xing}
 \end{aligned}$$



## Schematic of TAN and TAS instrumentation

- Fast gas ionization sampling chambers are located near the shower maxima inside the absorbers to take advantage of ;
  - multiplication of the collected charge by shower production and gas ionization
  - increased sensitivity to the most energetic IP collision fragments, shielding from soft particles
  - negligible impact on lattice space





## Concept for optimization of luminosity

(ref. H. Jostlien, Fermilab, TM-1253 (1984))

- An intentional transverse sweep of one beam introduces a time dependent modulation of luminosity

- $\varepsilon$  = error offset amplitude
- $d$  = intentional sweep amplitude

$$L \approx L_0 - L_0 \frac{\varepsilon d}{2\sigma_*^2} \cos(\omega t - \varphi); \varepsilon, d \ll \sigma_*$$

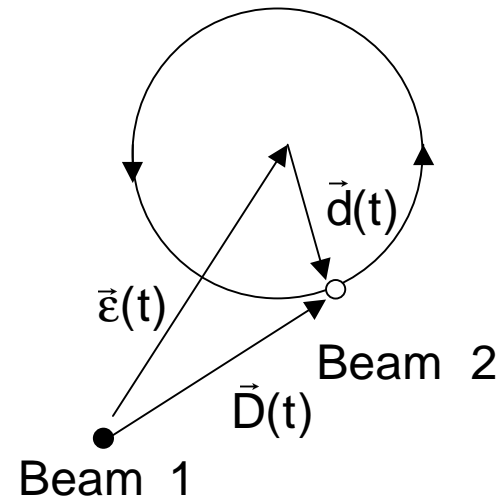
- Define the detector current

$$I(t) = e\alpha\varepsilon_{\text{det}}m\sigma_{\text{inel}}L$$

- Integrate to obtain the luminosity and error offset,  $0 < t < T$ ,

$$L_0 = \frac{\int_0^T I(t) dt}{e\alpha\varepsilon_{\text{det}}m\sigma_{\text{inel}}T};$$

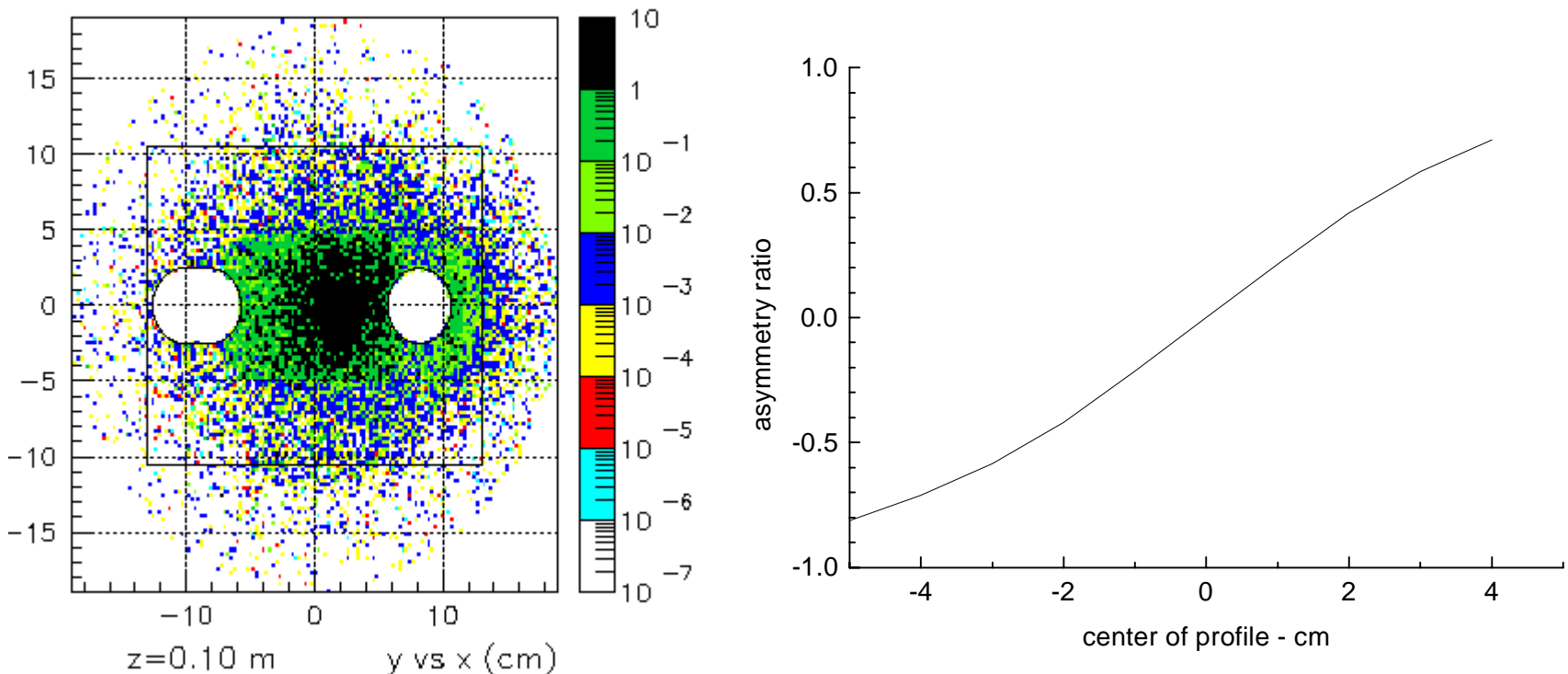
$$\vec{\varepsilon} = - \frac{\hat{e}_x \int_0^T \cos(\omega t) I(t) dt + \hat{e}_y \int_0^T \sin(\omega t) I(t) dt}{\left( \frac{d}{4\sigma_*^2} \right) e\alpha\varepsilon_{\text{det}}m\sigma_{\text{inel}}T}$$





The right-left asymmetry ratio is a sensitive function of the crossing angle

- TAN 142 m from IP, xing angle =  $\pm 150 \mu\text{rad}$

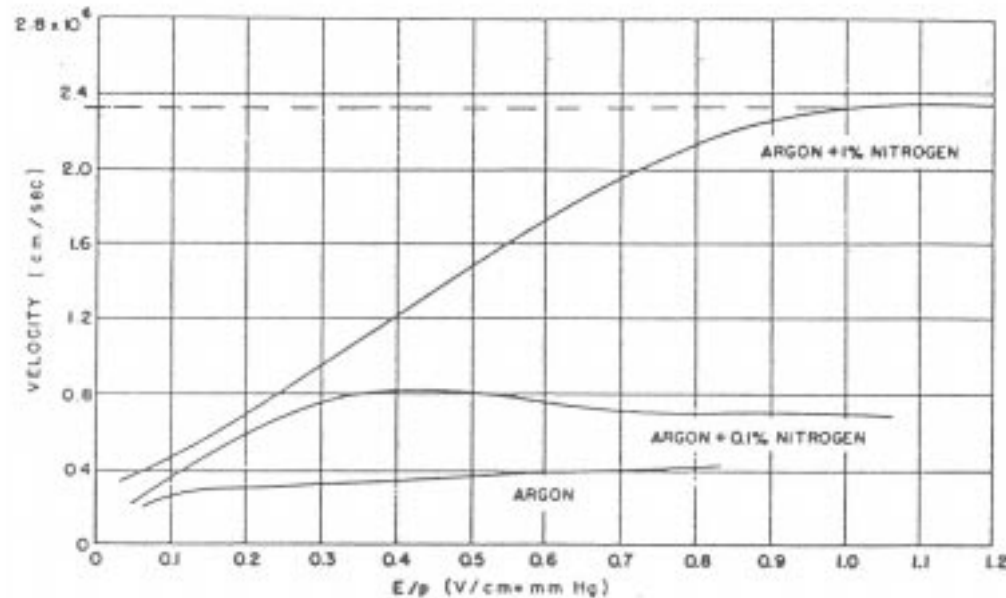


- Measurement of the asymmetry ratios at the positions of the TAS and TAN and on both sides of an IP may allow determination of IP pos. and xing angle



# Electron drift velocity, ionization chamber time resolution

(ref. T. Ferbel, "Expt. Techniques in HEP", pg. 107)

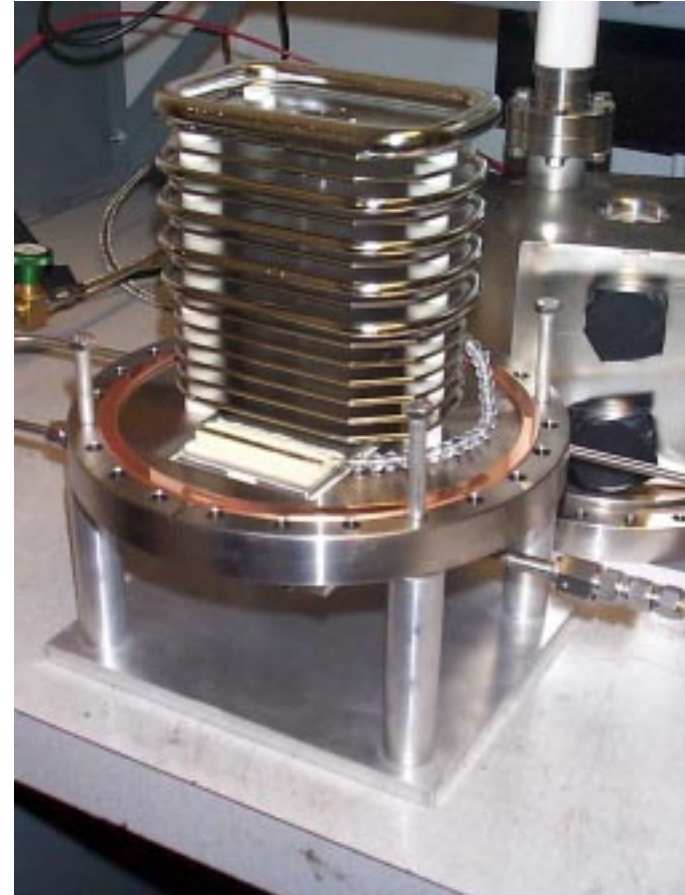
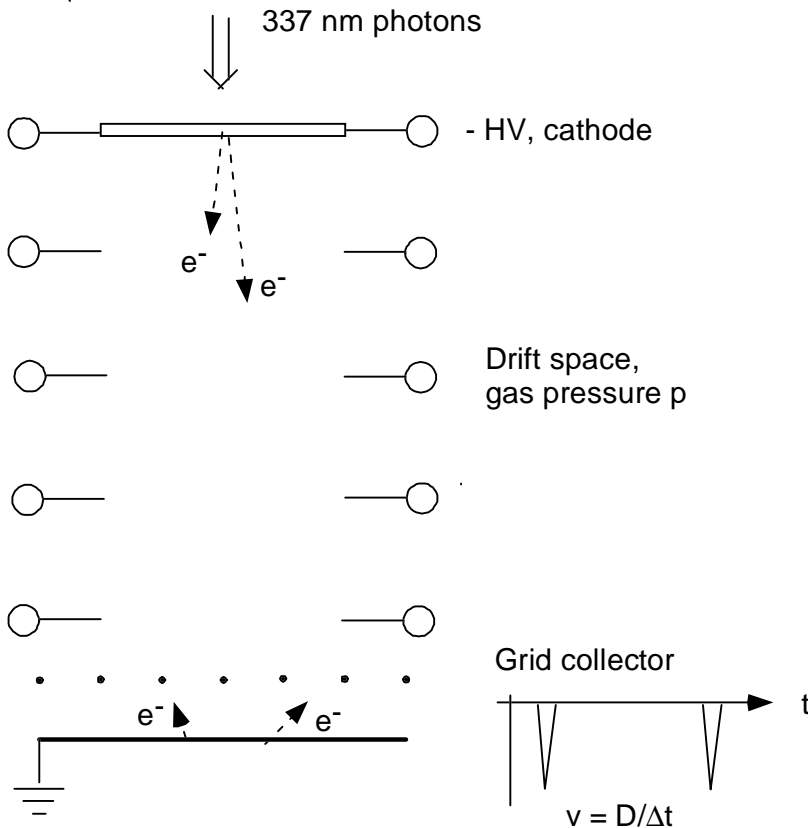


- $v = 2.3 \times 10^6$  cm/sec, gap = 0.5mm  $\Rightarrow t = 21.7$  nsec < 25 nsec  
bunch spacing
- $E/p = 1$  volt/cm-Torr,  $p = 4$  atmos, gap = 0.5 mm  $\Rightarrow 150$  V/gap



# Chamber for measurement of electron drift velocity

ref. M. Burks et al, NIM A385, 519. (1997)





## Ionization chamber constraints

- Beam-beam separation of the 7 TeV proton beams restricts the active area to

~ 80 mm x 80 mm

- Clearing time of 25 nsec between bunches sets the maximum gap at

~ 0.5 mm

- Matching the ionization chamber plus cable rise time to the pre-amp shaping time (2 ns) and requiring S/N ~ 6 requires

~ 48 gaps (6 series x 8 parallel)



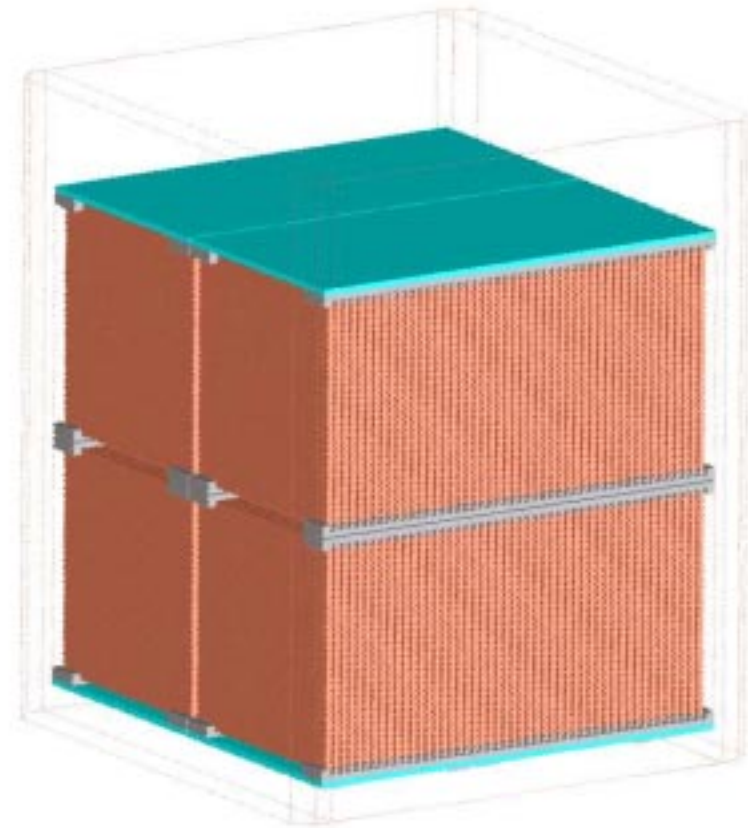
## Parameters for an ionization chamber module

Active area(1 quadrant)	40mm x 40mm	
Plate gap	0.5 mm	
No. of gaps	48 (electrically 6 series x 8 parallel)	
Capacitance/gap	28.3 pF	
Gas	Ar+N <sub>2</sub> (1%), 4x760 Torr	
Gap voltage	150 V	
Elec gap transit time	21.7 nsec	
Bunch freq/Rev freq	40.079 MHz/11.2455 kHz	
Bunch structure	12x(3x81+2x8+38) = 3,564	
Inel pp int/bunch xing@10 <sup>34</sup>	20	
mip per pp int (3 W/kgm)	268	
mip per bunch xing@10 <sup>34</sup>	5.35x10 <sup>3</sup>	
Electron/ion pairs/cm-mip	388	
Ioniz e <sup>-</sup> /pp int	5.2x10 <sup>3</sup> (1 gap)	4.2x10 <sup>4</sup> (8 gaps)
Ioniz e <sup>-</sup> /bunch xing@ 10 <sup>34</sup>	1.04x10 <sup>5</sup> (1 gap)	8.3x10 <sup>5</sup> (8 gaps)



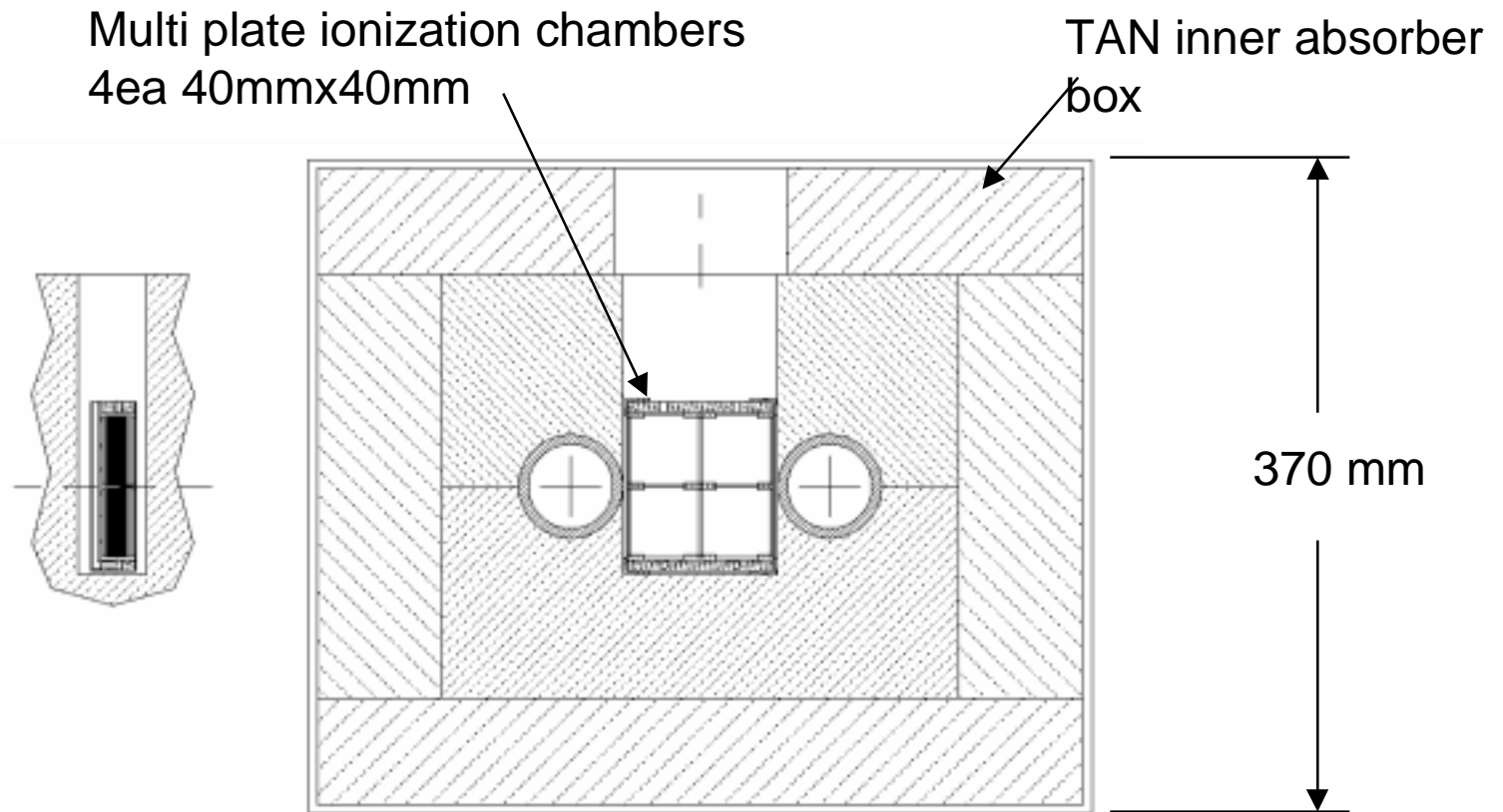
## Ionization chamber plate assembly

- beryllium copper plates
- ceramic and sapphire insulators
- plated strip on ceramic circuit board  
plate bias connections
- isolated instrumentation ground and local  
ground shielding enclosures





## Layout of Neutral Absorber ionization chamber





## Dynamic range

- The magnitude of charge collected in a single pp interaction ( $1/2 \times 4.2 \times 10^4 = 2.1 \times 10^4 \text{ e}^-$ ) is adequate for pulse shaping, digitizing and acquisition
- If the data are accumulated bunch by bunch, the dynamic range needed for front end electronics is a factor of  $\sim 100$  to cover luminosity from an arbitrarily low value up to  $2.5 \times 10^{34} \text{ cm}^2 \text{ sec}^{-1}$  (50 pp interactions per bunch crossing)
- The dynamic range needed increases linearly with the bunch accumulation factor (x1 for 40 MHz, x2 for 20 MHz etc)
- The S/N ratio of front end electronics ( $\sim 6$  for 1 pp interaction) is chosen so that integration times are dominated by the statistics of particle production at the IP



Increasing gas pressure is the main route to increasing the electronic signal to noise ratio

$$\left(\frac{S}{N}\right)^2 = \frac{N_{\text{gap}} Q_{\text{gap}}^2}{2kTC_{\text{gap}} \left(\frac{a_1 a_2}{\beta}\right)^{1/2} * \sigma^2}$$

- $C_{\text{gap}}$  is fixed by transit time and geometry considerations
- Ballistic deficit is constrained to  $\sigma \sim 2$  by pulse shaper time  $\sim$  few ns, transit time  $\sim$  20 ns and bunch separation  $\sim$  25 ns
- Sensitivity to the pre-amplifier parameters ( $a_1$ ,  $a_2$ ,  $\beta$ ) is low
- S/N is independent of the parallel-series connection of gaps ( $N_{\text{gap}} = n_1 n_2$ )

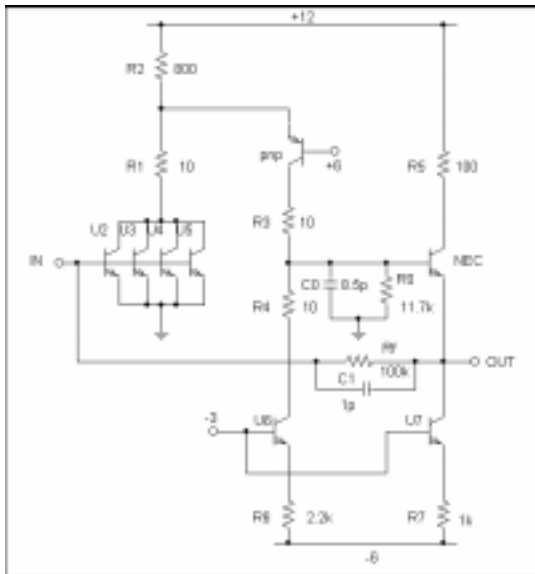
=> increased S/N is primarily sensitive to the collected charge or equivalently, the gas pressure of the ionization chamber



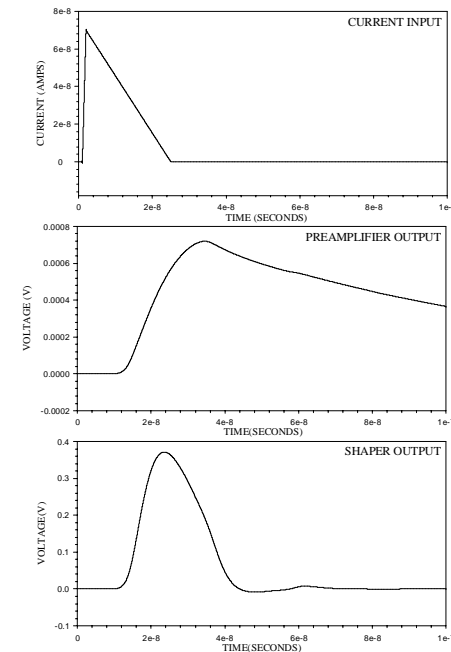
The designs for the analog preamplifier and pulse shaper have been modeled with real device characteristics

- 2 m cable,  $C_D = 40$  pF detector capacitance,  $ENC = 3363 e^-$
- $S/N = (0.5 \times 4.2 \times 10^4) / 3363 = 6.2$  for single pp interaction
- $\Rightarrow$  8 plates in parallel x 6 in series, 4 atmos

PREAMPLIFIER SCHEMATIC



REAL AMPLIFIER WITH CABLE





Integration times are sufficiently short to be practical even for the lowest luminosity envisioned (TOTEM)

- Bunch by bunch measurements increase the integration times by the number of bunches (x2835 for  $L = 10^{34}$ , x36 for TOTEM)
- The practical sweep frequency needed for beam-beam separation measurements (1 Hz ?) will determine the integration time at the highest luminosity

		Integration time(sec/turns)		
$L$ $\text{cm}^{-2}\text{s}^{-1}$	$\frac{\sigma_L}{L} = 0.01$	$\sigma_\varepsilon = 0.1\sigma^*$	$\sigma_\psi = 1\mu\text{rad}$	$\sigma_{ax}^* = \sigma^*$
$10^{34}$	$6.2 \times 10^{-5} / 0.7$	$1.0 \times 10^{-3} / 11$	$2.55 \times 10^{-4} / 2.9$	$3.8 \times 10^{-3} / 42.6$
$10^{28}$	$62 / 7.0 \times 10^5$	$1.0 \times 10^3 / 1.1 \times 10^7$	$2.55 \times 10^2 / 2.9 \times 10^6$	$3.8 \times 10^3 / 4.26 \times 10^7$



## Bringing the beams into initial collision

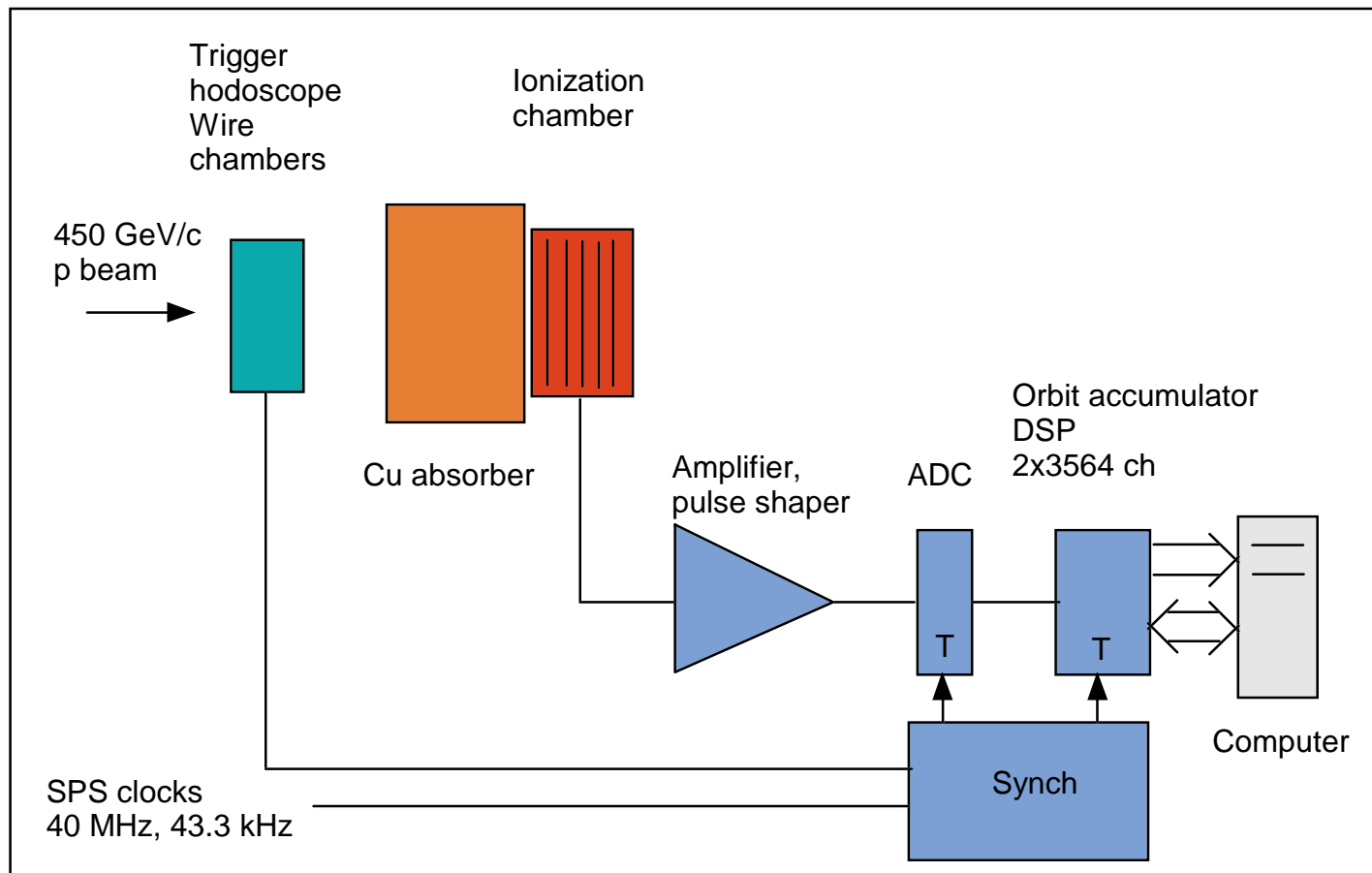
- One approach - start with a coarse grid map with successively finer mesh followed by application of the beam sweeping method with successively smaller radii
- An extreme example - TOTEM,  $L = 10^{28} \text{cm}^{-2} \text{s}^{-1}$

Domain	Grid size	$\delta L/L$	Integration time (sec)
$\pm 4\sigma \times \pm 4\sigma$	$2\sigma$	10%	15.5
$\pm 2\sigma \times \pm 2\sigma$	$1\sigma$	5%	62.5
Sweep radius		$\sigma_\epsilon$	
$1\sigma$	NA	$1\sigma$	10
$.5\sigma$	NA	$.5\sigma$	40
$.2\sigma$	NA	$.2\sigma$	250
$.1\sigma$	NA	$.1\sigma$	1000

- Total integration time allowing for two iterations of each beam sweep = approximately 45 min



## Schematic of test setup to be installed in the SPS H4 beam area in summer 2000





## Summary

- Instrumenting the TAN and TAS absorbers can provide a useful tool for optimizing the luminosity of the LHC
- Backgrounds and systematic effects appear to be small compared to the anticipated signals
- It is feasible that an Ar 1%N<sub>2</sub> ionization chamber can meet the requirements for an LHC luminosity monitor
  - LHC Lumi workshop 15-16 Apr 1999 at CERN
  - CDR 16-17 Sep 1999 at LBNL
- A scheduled run in an SPS test beam will use 450 GeV/c protons to simulate hadrons incident on the IR absorbers of LHC